

Heavy Flavor Spectroscopy at BABAR

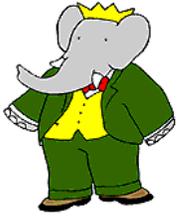
A. Rakitin

on behalf of BABAR Collaboration

DIS 2011

*XIX International Workshop on Deep Inelastic Scattering
and Related Subjects*

Newport News, Virginia, April 11-15, 2011

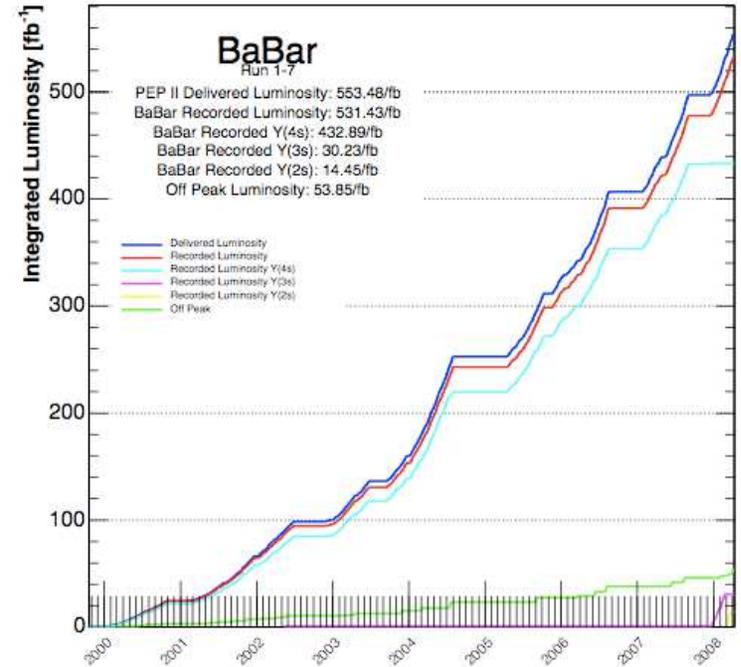


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Short Introduction:



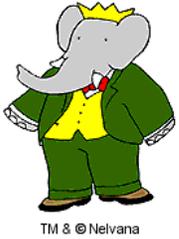
- ➔ BABAR detector located at PEP-II linear e^+e^- collider at SLAC National Laboratory
- ➔ Operated since Oct 1999 until Apr 2008
- ➔ Collected large datasets:
 - $467 \times 10^6 \Upsilon(4S)$ (433 fb^{-1})
 - $122 \times 10^6 \Upsilon(3S)$ (30 fb^{-1})
 - $99 \times 10^6 \Upsilon(2S)$ (14 fb^{-1})
 - off-peak sample (54 fb^{-1})
 - small sample taken above $\Upsilon(4S)$ ($\sim 4 \text{ fb}^{-1}$)
- ➔ **Plenty of data for heavy flavor spectroscopy!**



Additional advantages:

- Relatively low track multiplicity
- Great particle ID
- Precise energy resolution
- Possibility to use recoil technique

BABAR is an excellent place for spectroscopy analyses!!!

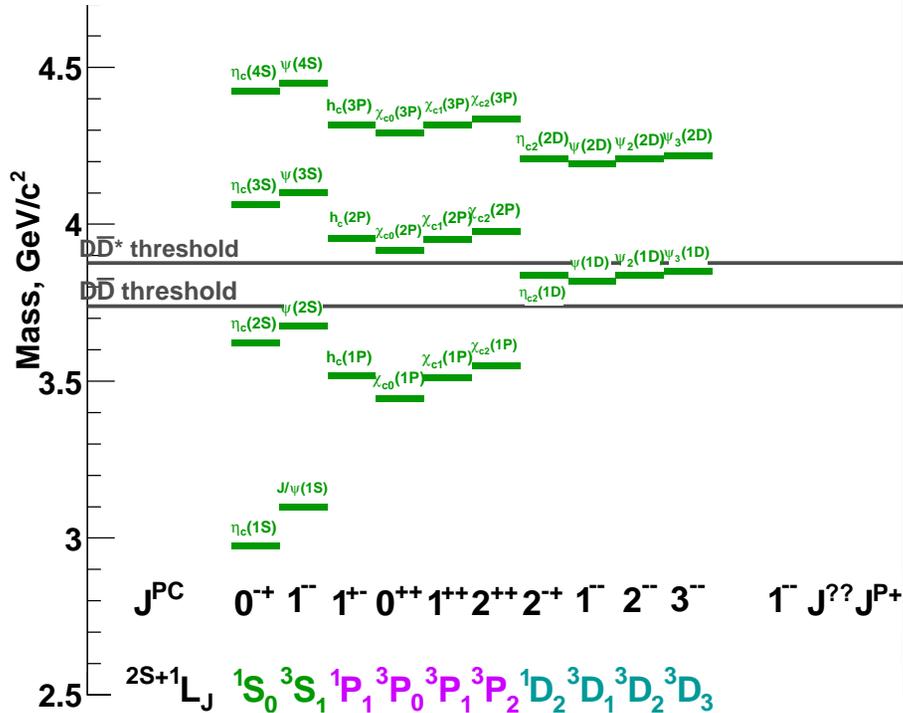


Heavy Flavor Spectroscopy

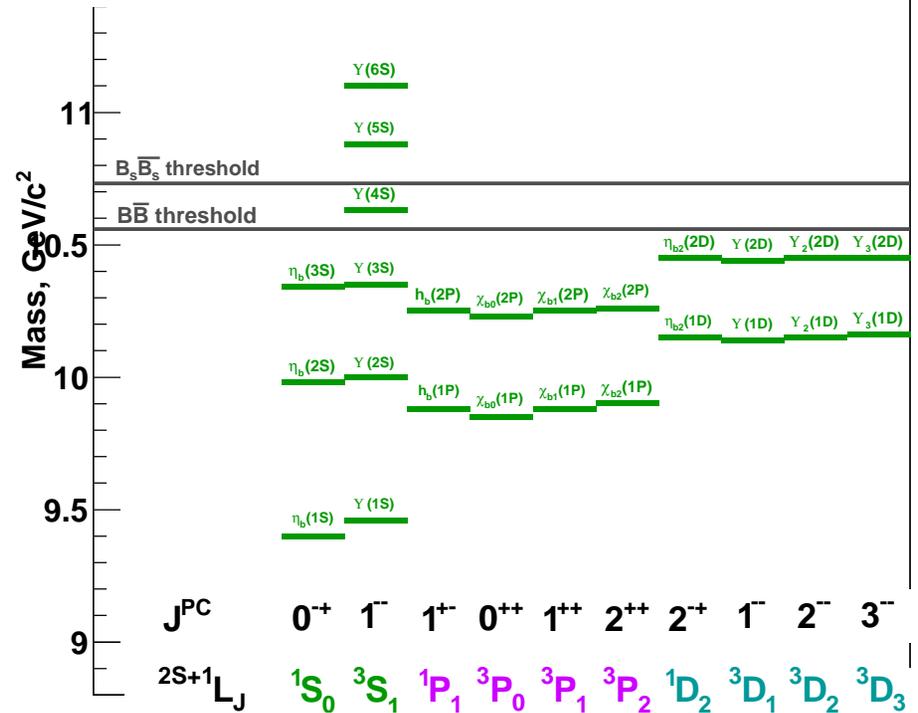


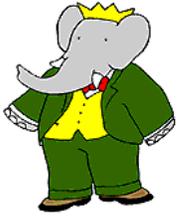
Predicted charmonium and bottomonium spectra:

Green - predicted masses [PRD72,054026(2005)]



Green - predicted masses [PRD32,189(1985)]



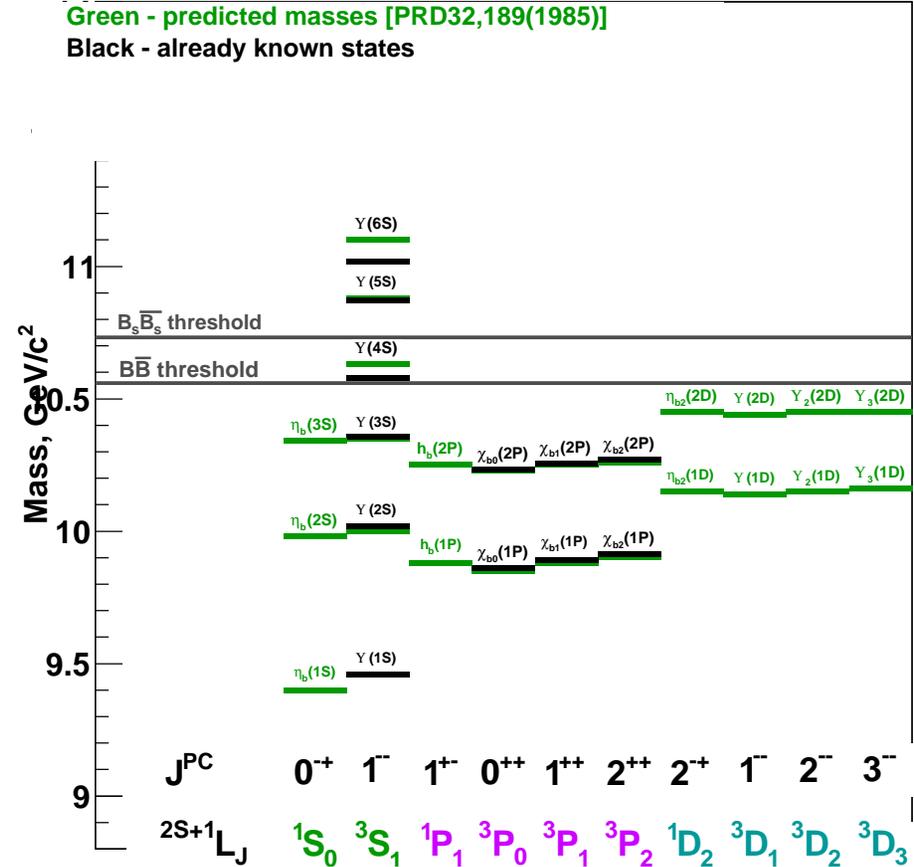
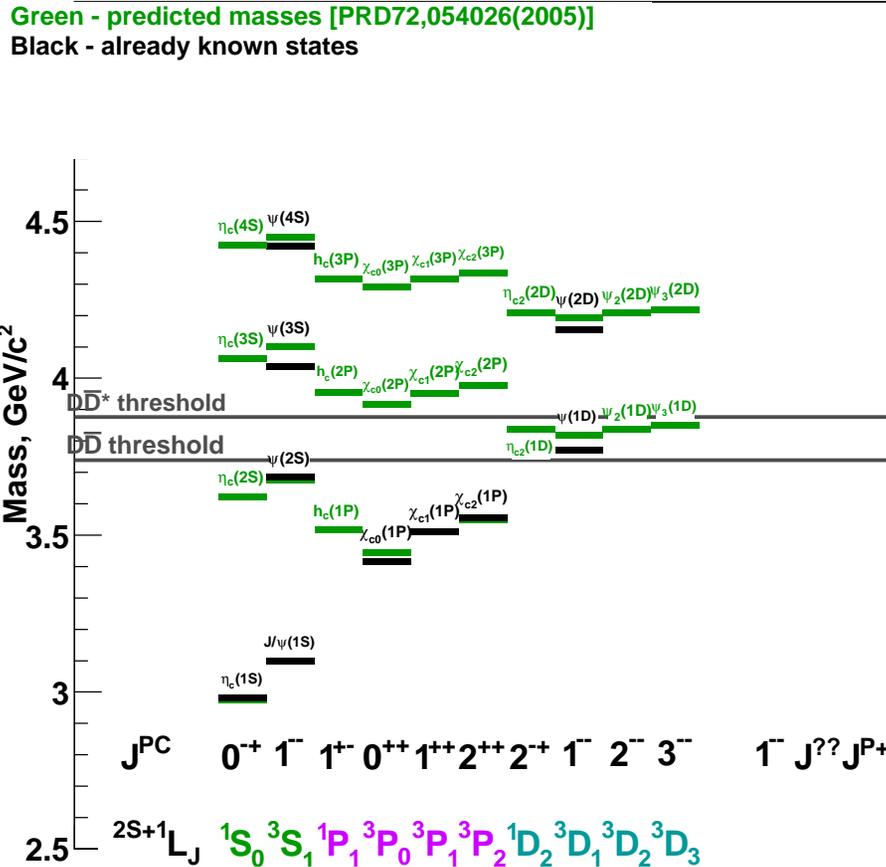


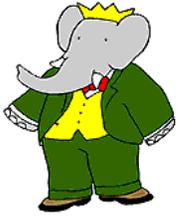
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Predicted and well-known experimental states:





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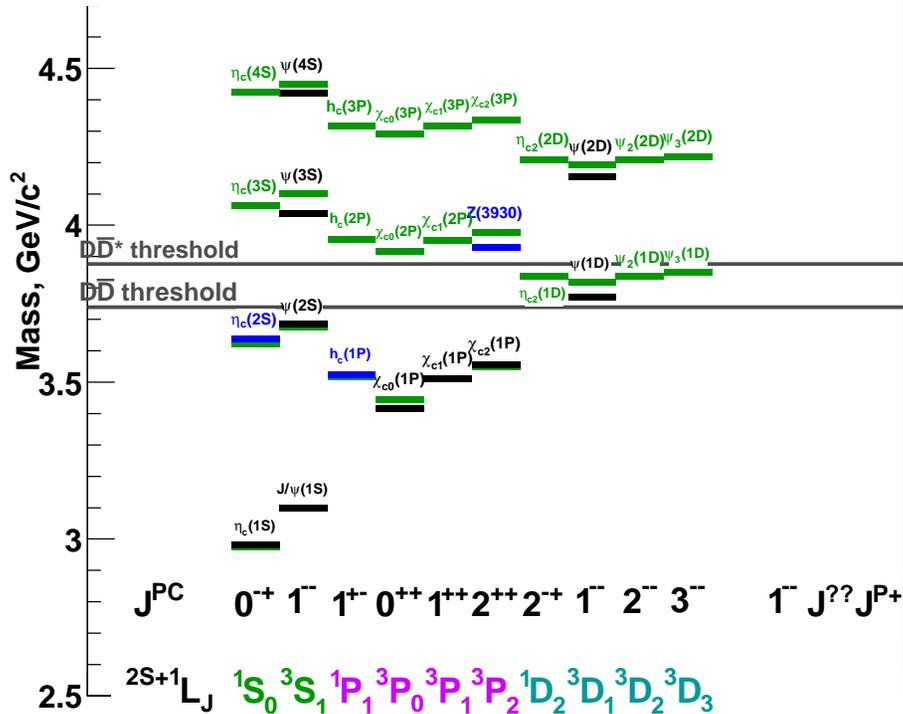


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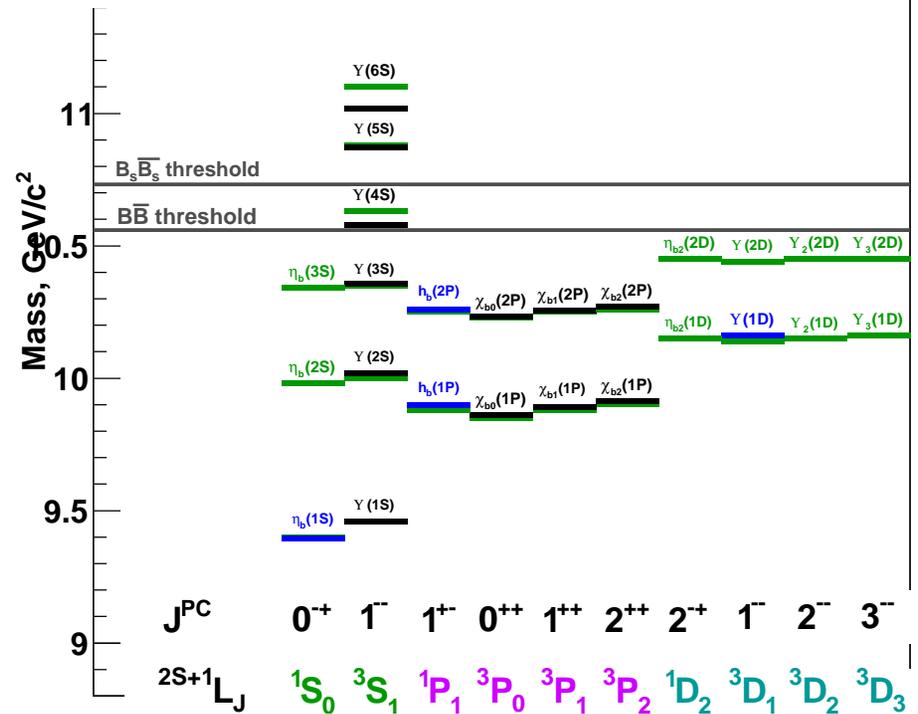
Predicted and well-known + recently discovered expected states:

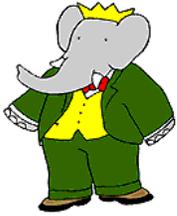
- Charmonium: $\eta_c(2S)$, $h_c(1P)$, $\chi_{c2}(2P) = Z(3930)$
- Bottomonium: $\eta_b(1S)$, $h_b(1P)$, $h_b(2P)$, $\Upsilon(1D)$

Green - predicted masses [PRD72,054026(2005)]
 Black - already known states
 Blue - recently discovered, compliant with $q\bar{q}$



Green - predicted masses [PRD32,189(1985)]
 Black - already known states
 Blue - recently discovered





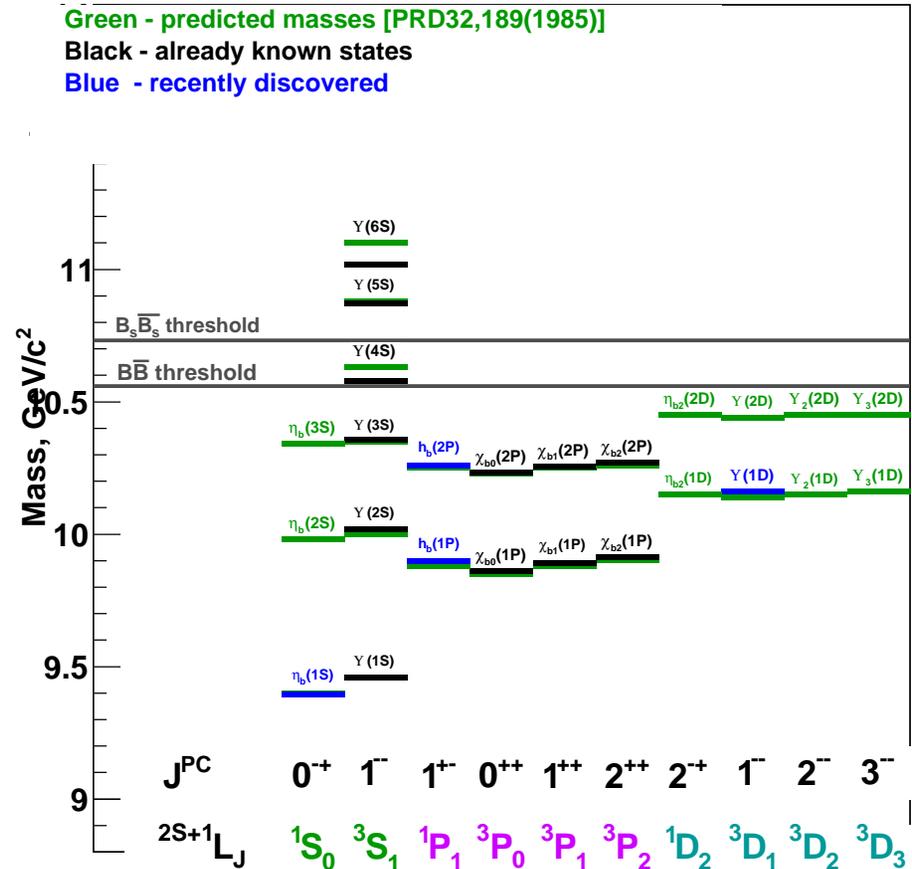
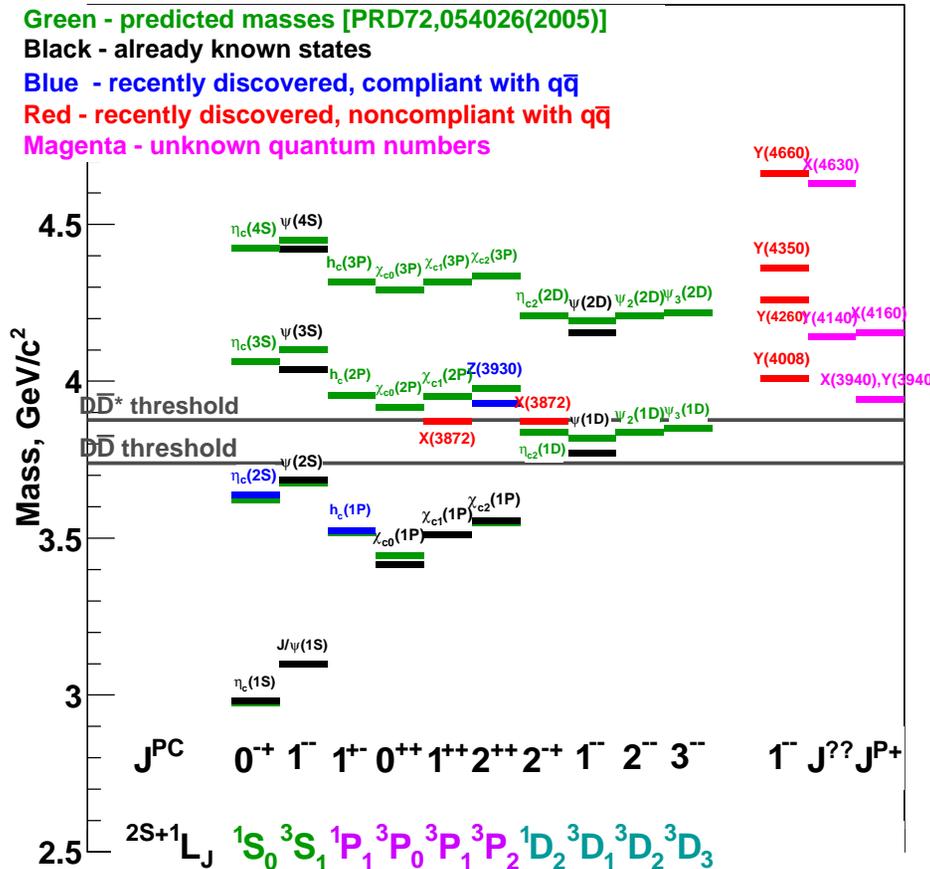
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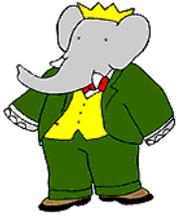


Heavy Flavor Spectroscopy

Predicted and well-known + recent + unexpected surprises:

- Expected: $\eta_c(2S)$, $h_c(1P)$ etc
- Not expected: $X(3872)$, $Y(4260)$, $Y(4140)$, $X(3940)$, $Y(3940)$ etc





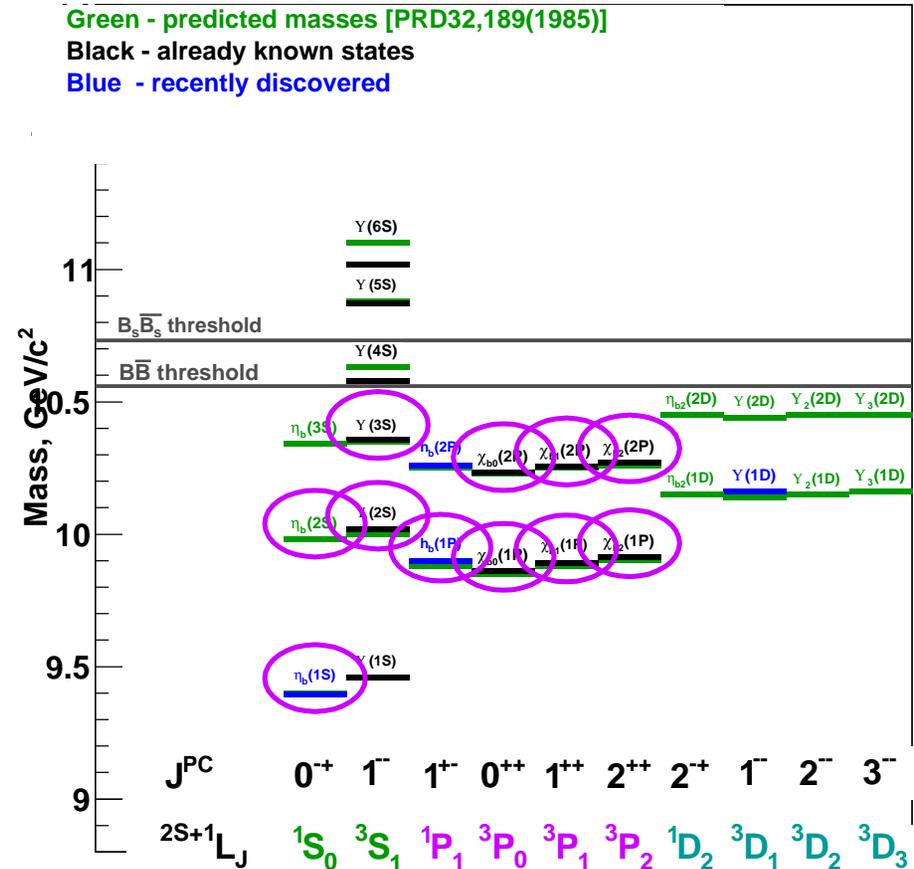
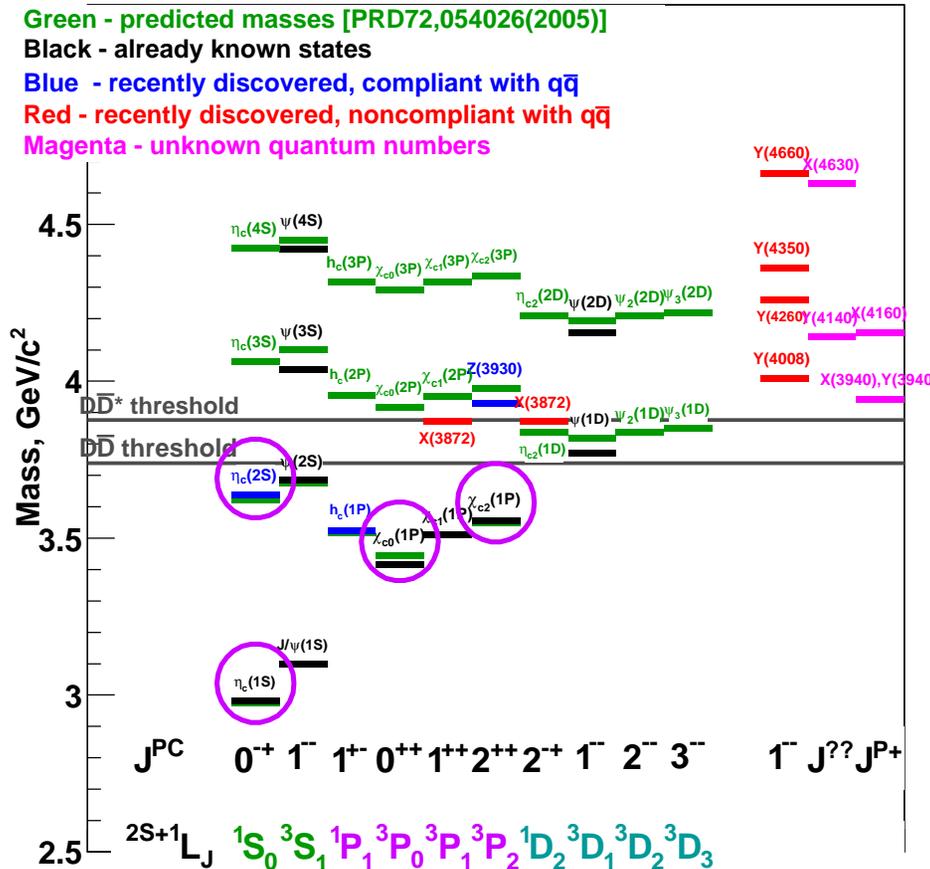
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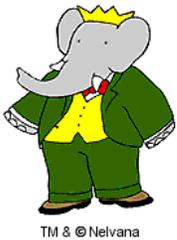


Heavy Flavor Spectroscopy

BABAR analyses covered in this talk involve the following states:

- Measurements of $\eta_c(1S, 2S)$, $\chi_{c0,c2}(1P)$, $\chi_{bJ}(1P, 2P)$ decays
- First observation of $h_b(1P)$ and searches for $\eta_b(1S, 2S)$





BABAR Recent Analyses Overview:

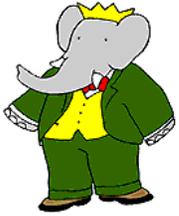


☞ Charmonium:

- Study of $\eta_c(2S)$ and other charmonium states produced in $\gamma\gamma$ collisions and decaying into $K_S K^\pm \pi^\mp$ and $K^+ K^- \pi^+ \pi^- \pi^0$

☞ Bottomonium:

- Study of radiative transitions from $\Upsilon(2S)$ and $\Upsilon(3S)$ using converted photons
 - Measurement of $\mathcal{B}(\chi_{b1,2}(1P, 2P) \rightarrow \gamma\Upsilon(1S))$ and $\mathcal{B}(\chi_{b1,2}(2P) \rightarrow \gamma\Upsilon(2S))$
 - Search for $\eta_b(1S, 2S)$ states
- Search for $h_b(1P)$ bottomonium state in transitions $\Upsilon(3S) \rightarrow \pi^0 h_b$ and $\Upsilon(3S) \rightarrow \pi^+ \pi^- h_b$



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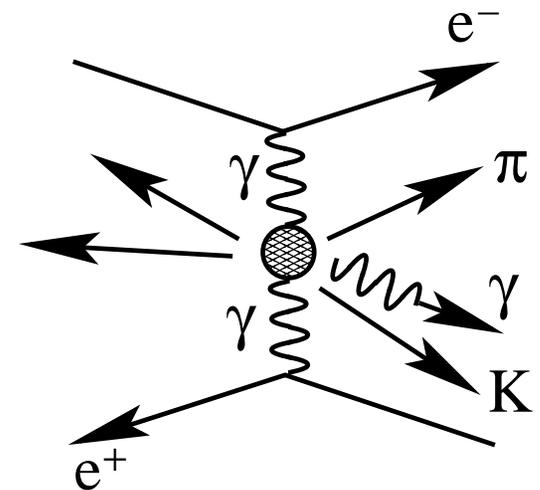
$\eta_c(1S)$ and $\eta_c(2S)$

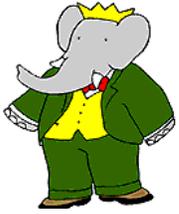
Motivation:

- $\eta_c(1S)$ has already been observed in decays with 4-track final states
- Until recently $\eta_c(2S)$ has only been observed in exclusive decay to $K\bar{K}\pi$
- Precise measurement of $m(\eta_c(2S))$ will help discriminate between different charmonium models

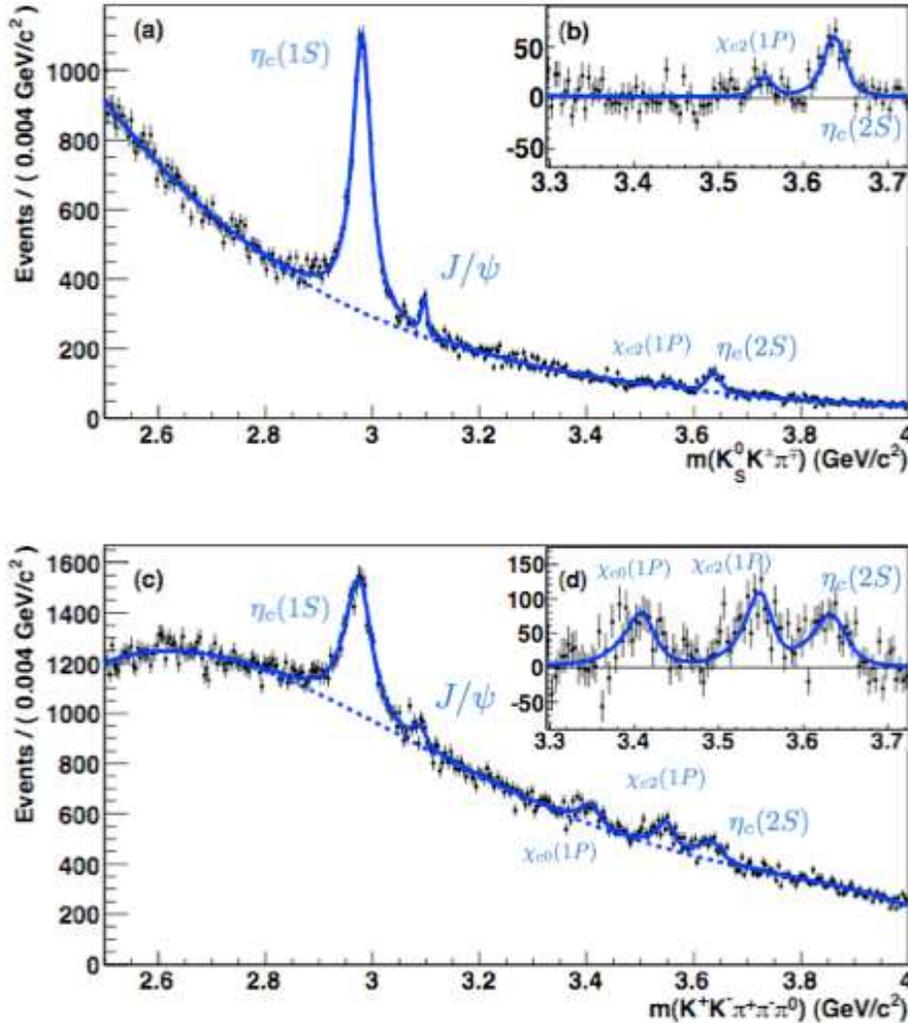
Analysis Strategy:

- Use virtually **all** BABAR data:
 - 520 fb⁻¹ collected at $\Upsilon(4S)$, $\Upsilon(3S)$, $\Upsilon(2S)$ and off-peak
- Production: two-photon collisions $e^+e^- \rightarrow \gamma\gamma e^+e^-$
 - Only particles with even $J^{\pm+}$ or odd J^{++} with $J > 1$ are allowed
- Final states $\gamma\gamma e^+e^- \rightarrow K^+K^-\pi^+\pi^-\pi^0 e^+e^-$ and $K_S K^\pm \pi^\mp e^+e^-$
- Outgoing e^+ and e^- are not detected

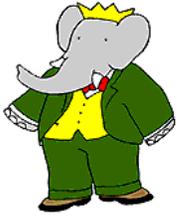




$\eta_c(1S)$ and $\eta_c(2S)$



- Top: $K_S K^\pm \pi^\mp$,
bottom: $K^+ K^- \pi^+ \pi^- \pi^0$
- Insets: background-subtracted distributions
- As expected, we see peaks for:
 - $\eta_c(1S)$, $\chi_{c2}(1P)$, $\eta_c(2S)$ in $K_S K^\pm \pi^\mp$ signature
 - $\eta_c(1S)$, $\chi_{c0}(1P)$, $\chi_{c2}(1P)$, $\eta_c(2S)$ in $K^+ K^- \pi^+ \pi^- \pi^0$ signature
 - $\chi_{c0}(1P) \nrightarrow K_S K^\pm \pi^\mp$
- Possible peak for $Z(3930) = \chi_{c2}(2P)$ is not observed in either signature



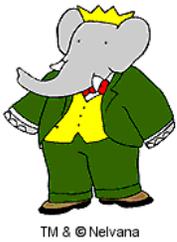
$\eta_c(1S)$ and $\eta_c(2S)$

Final results:

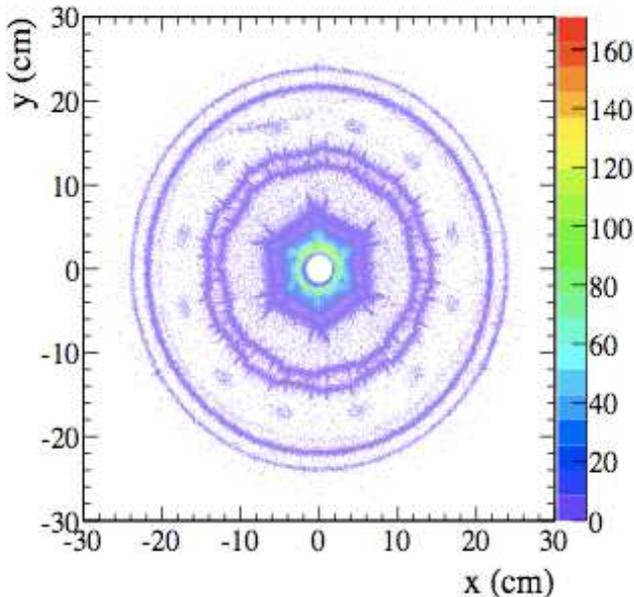
$$m(\eta_c(2S)) = 3638.5 \pm 1.5 \pm 0.8 \text{ MeV}/c^2$$

$$\Gamma(\eta_c(2S)) = 13.4 \pm 4.6 \pm 3.2 \text{ MeV}$$

Process	$\Gamma_{\gamma\gamma} \times \mathcal{B}$ (keV)
$\eta_c(1S) \rightarrow K \bar{K} \pi$	$0.386 \pm 0.008 \pm 0.021$
$\eta_c(2S) \rightarrow K \bar{K} \pi$	$0.041 \pm 0.005 \pm 0.006$
$Z(3930) \rightarrow K \bar{K} \pi$	$< 2.1 \times 10^{-3}$
$\eta_c(1S) \rightarrow K^+ K^- \pi^- \pi^- \pi^0$	$0.190 \pm 0.008 \pm 0.027$
$\eta_c(2S) \rightarrow K^+ K^- \pi^- \pi^- \pi^0$	$0.030 \pm 0.003 \pm 0.005$
$Z(3930) \rightarrow K^+ K^- \pi^- \pi^- \pi^0$	$< 3.4 \times 10^{-3}$

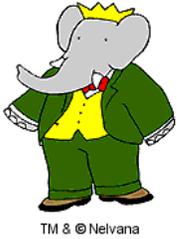


Radiative transitions from $\Upsilon(2S, 3S)$ with converted photons



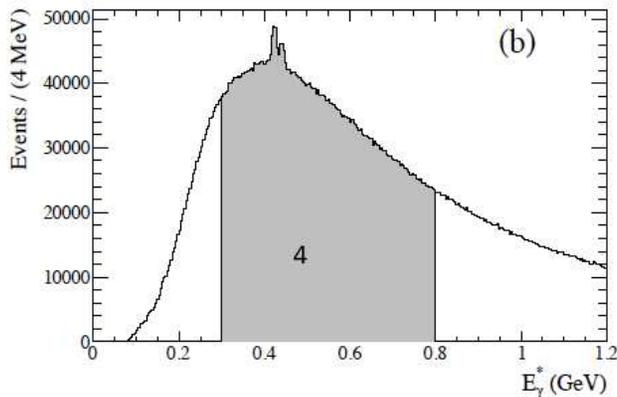
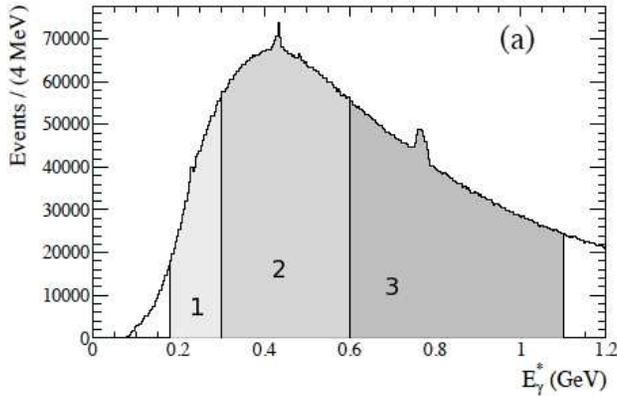
BABAR detector as seen
by converted photons

- Using converted photons $\gamma \rightarrow e^+e^-$ greatly improves energy resolution
- Select e^+e^- tracks with invariant mass close to zero
- The signal appears as peaks in inclusive photon spectrum
 - Reminder:
$$E(\gamma)_{CM} = \left((\sqrt{s})^2 - m_{final\ state}^2 \right) / (2\sqrt{s})$$
- The analysis involves:
 - Measurement of $\mathcal{B}(\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(2S))$,
 $\mathcal{B}(\chi_{bJ}(1P, 2P) \rightarrow \gamma\Upsilon(1S))$
 - Observation of $\Upsilon(3S) \rightarrow \gamma\chi_{b0,2}(1P)$
 - Search for $\eta_b(1S)$ and $\eta_b(2S)$



Radiative transitions from $\Upsilon(2S, 3S)$ with converted photons

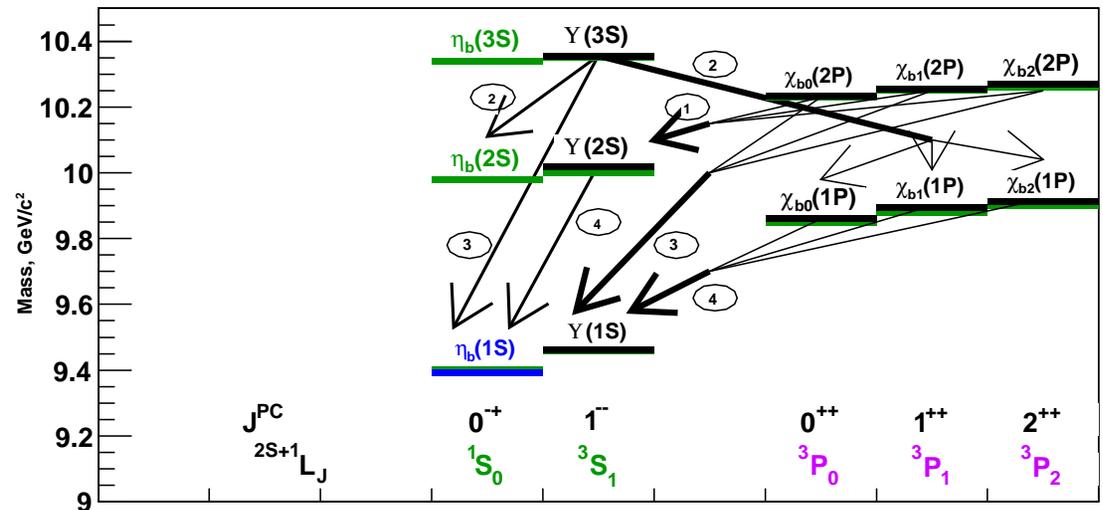
Raw inclusive converted photon energy spectrum:

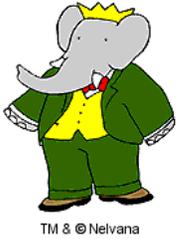


Top plot $\Upsilon(3S)$, bottom $\Upsilon(2S)$

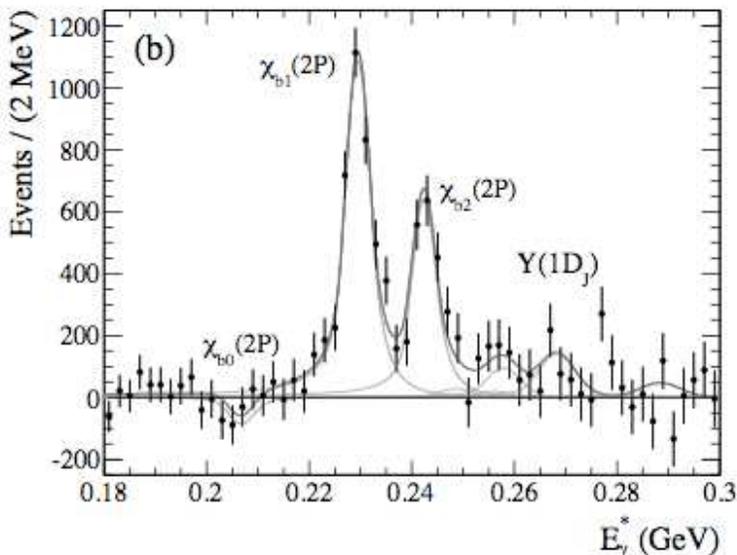
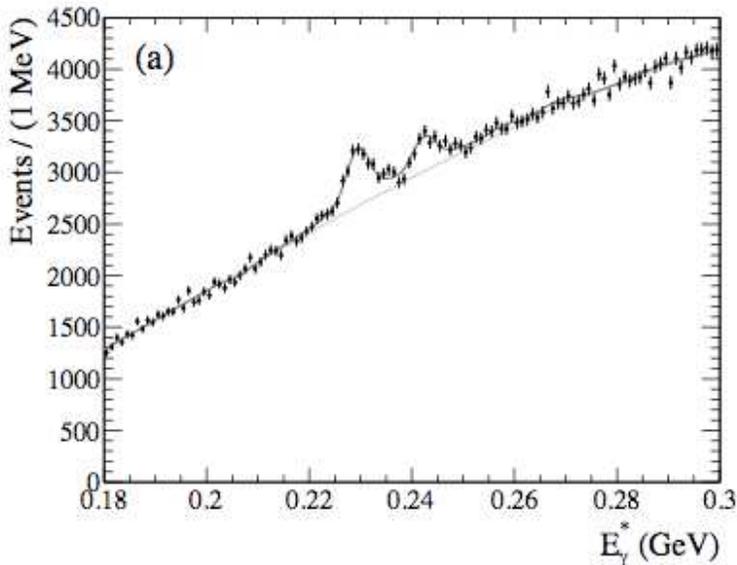
Left plots: shaded areas (of interest):

- 1) $\Upsilon(3S)$ data: $180 < E_{CM}(\gamma) < 300$ MeV
- 2) $\Upsilon(3S)$ data: $300 < E_{CM}(\gamma) < 600$ MeV
- 3) $\Upsilon(3S)$ data: $600 < E_{CM}(\gamma) < 1100$ MeV
- 4) $\Upsilon(2S)$ data: $300 < E_{CM}(\gamma) < 800$ MeV



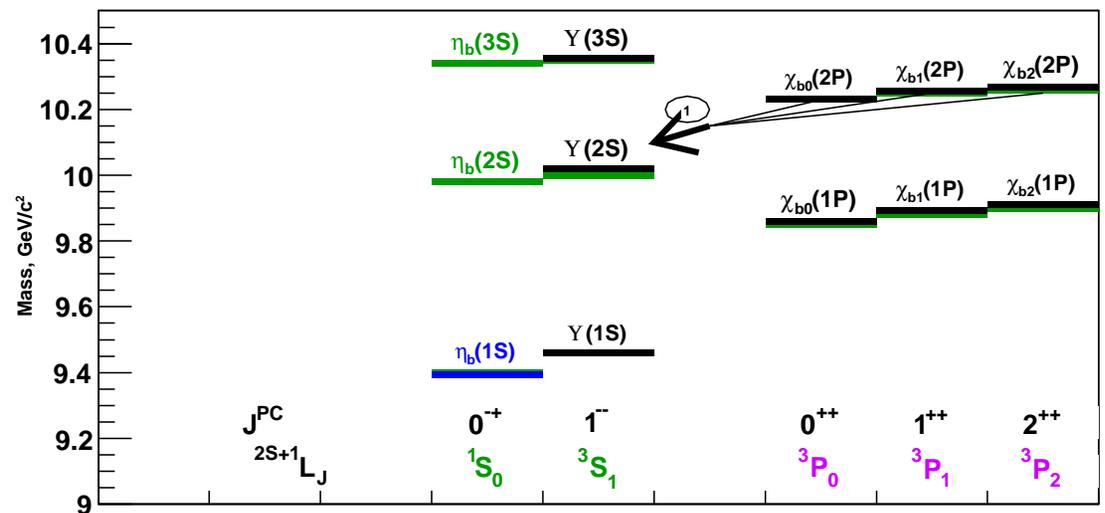


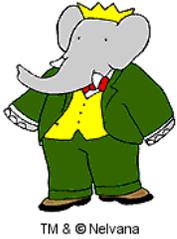
Radiative transitions from $\Upsilon(2S, 3S)$ with converted photons



- First region of interest: $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(2S)$
- **Left plots:** before (top) and after (bottom) background subtraction
- Clearly seen peaks for $\chi_{bJ}(2P)$ and even a hint for $\Upsilon(1D)$

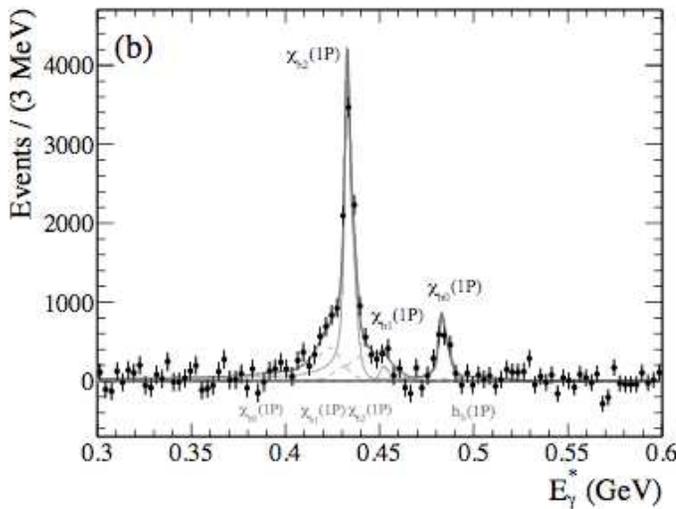
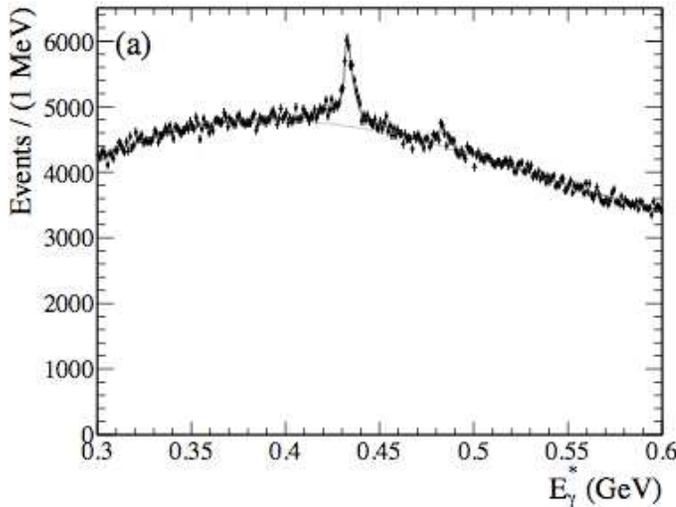
Transition	E_γ^* (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%)		
				BABAR	CUSB	CLEO
$\chi_{b0}(2P) \rightarrow \gamma\Upsilon(2S)$	205.0	-347 ± 209	0.105	$-4.9 \pm 2.9^{+0.7}_{-0.8} \pm 0.5$ (< 2.9)	3.6 ± 1.6	< 5.2
$\chi_{b1}(2P) \rightarrow \gamma\Upsilon(2S)$	229.7	4294 ± 251	0.152	$19.5 \pm 1.1^{+1.1}_{-1.0} \pm 1.9$	13.6 ± 2.4	21.1 ± 4.5
$\chi_{b2}(2P) \rightarrow \gamma\Upsilon(2S)$	242.3	2462 ± 243	0.190	$8.6^{+0.9}_{-0.8} \pm 0.5 \pm 1.1$	10.9 ± 2.2	9.9 ± 2.7



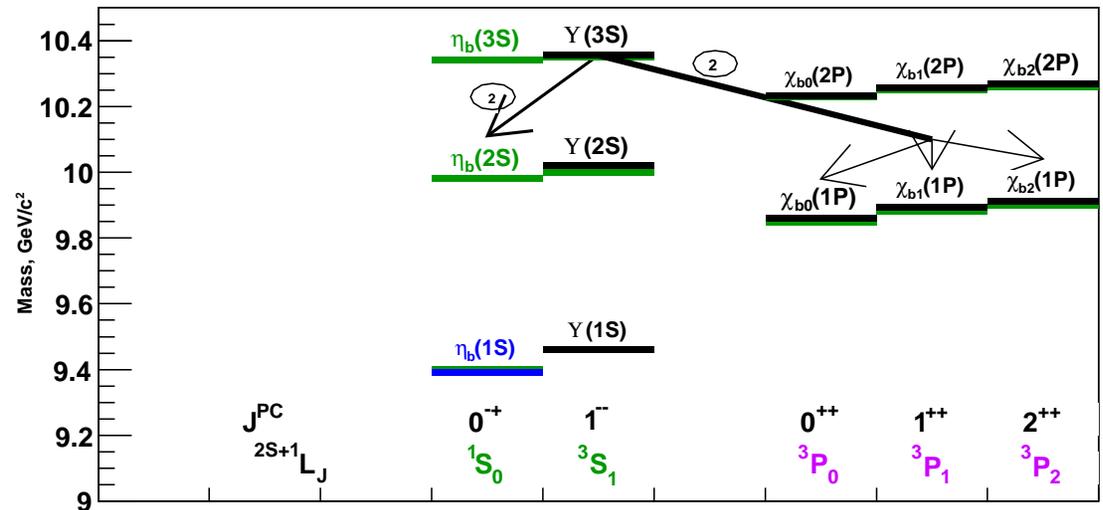


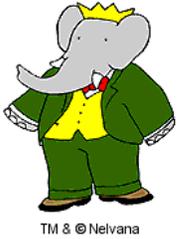
Radiative transitions from $\Upsilon(2S, 3S)$ with converted photons

- Second region of interest: $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(1P)$ and $\Upsilon(3S) \rightarrow \gamma\eta_b(2S)$
- **Left plots:** before (top) and after (bottom) background subtraction
- Clearly seen peaks for $\chi_{bJ}(1P)$
- **Observation and most precise measurement of $\Upsilon(3S) \rightarrow \gamma\chi_{b0,2}(1P)$**



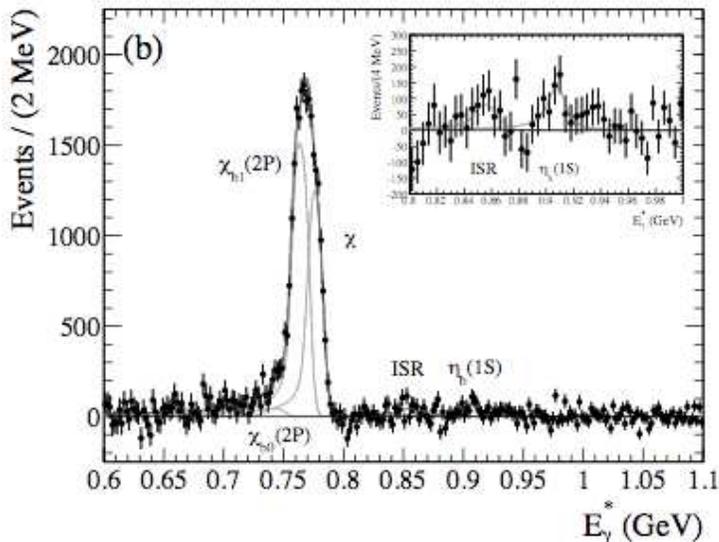
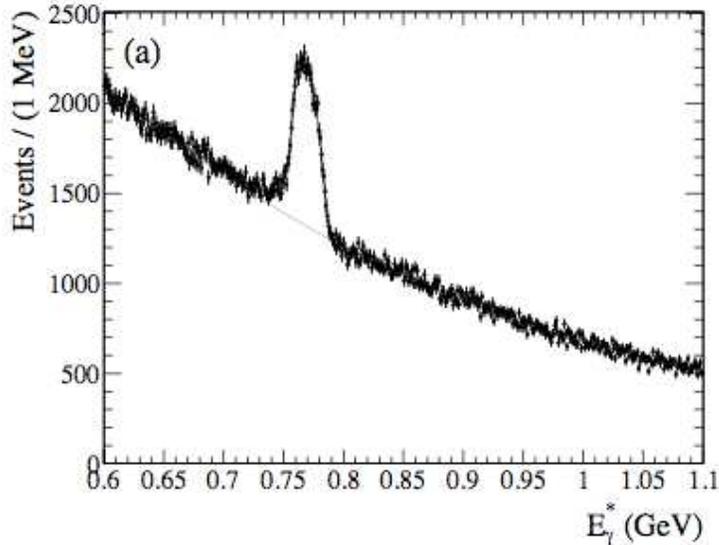
Transition	E_γ^* (MeV)	Yield	ϵ (%)	Derived Branching Fraction ($\times 10^{-3}$)	
				BABAR	CLEO
$\Upsilon(3S) \rightarrow \gamma\chi_{b2}(1P)$	433.1	9699 ± 318	0.794	$10.6 \pm 0.3 \pm 0.6$	7.7 ± 1.3
$\Upsilon(3S) \rightarrow \gamma\chi_{b1}(1P)$	452.2	483 ± 315	$0.818 \pm 0.3^{+0.2}_{-0.1}$	< 1.1	1.6 ± 0.5
$\Upsilon(3S) \rightarrow \gamma\chi_{b0}(1P)$	483.5	2273 ± 307	0.730	$2.7 \pm 0.4 \pm 0.2$	3.0 ± 1.1



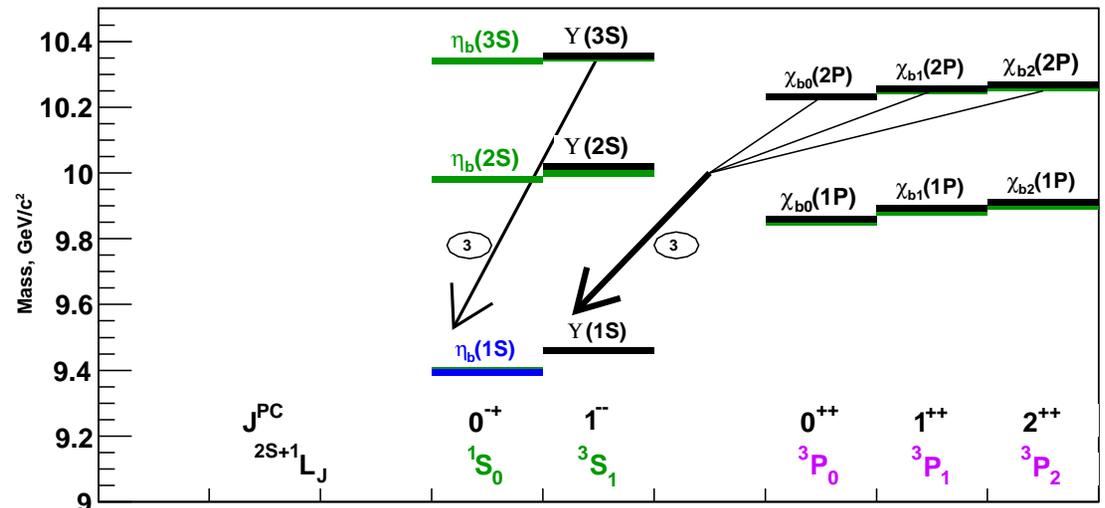


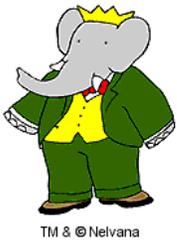
Radiative transitions from $\Upsilon(2S, 3S)$ with converted photons

- Third region of interest: $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(1S)$ and $\Upsilon(3S) \rightarrow \gamma\eta_b(1S)$
- **Left plots:** before (top) and after (bottom) background subtraction
- Clearly seen peaks for $\chi_{bJ}(2P)$ and no evidence for $\eta_b(1S)$ (inset)



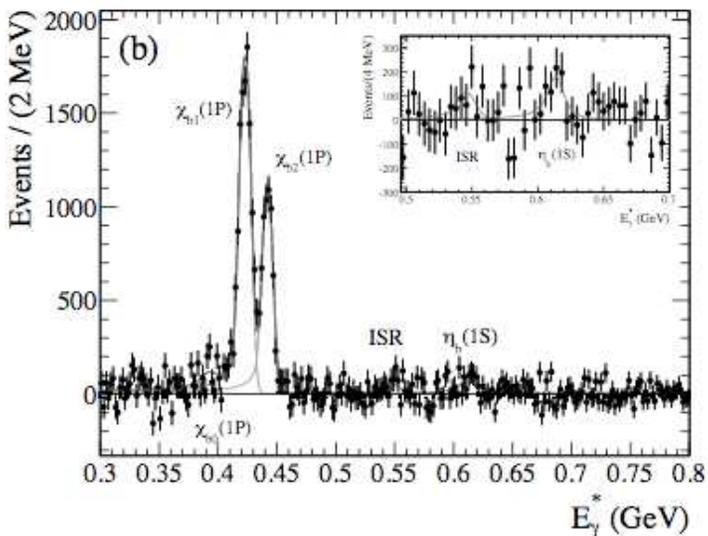
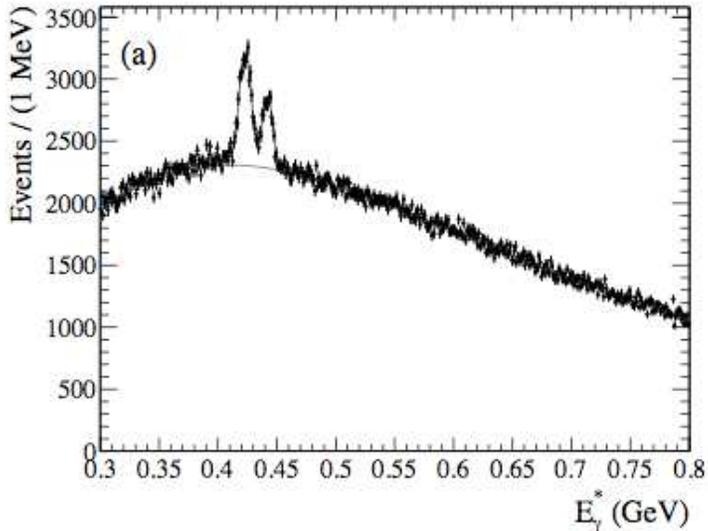
Transition	E_γ^* (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%)		
				BABAR	CUSB	CLEO
$\chi_{b0}(2P) \rightarrow \gamma\Upsilon(1S)$	742.7	469^{+260}_{-259}	1.025	$0.7 \pm 0.4^{+0.2}_{-0.1} \pm 0.1$ (< 1.2)	< 1.9	< 2.2
$\chi_{b1}(2P) \rightarrow \gamma\Upsilon(1S)$	764.1	14965^{+381}_{-383}	1.039	$9.9 \pm 0.3 \pm 0.4 \pm 0.9$	7.5 ± 1.3	10.4 ± 2.4
$\chi_{b2}(2P) \rightarrow \gamma\Upsilon(1S)$	776.4	11283^{+384}_{-385}	1.056	$7.1 \pm 0.2 \pm 0.3 \pm 0.9$	6.1 ± 1.2	7.7 ± 2.0
$\Upsilon(3S) \rightarrow \gamma\eta_b(1S)$	$907.9 \pm 2.8 \pm 0.9$	933^{+263}_{-262}	1.388	$0.059 \pm 0.016^{+0.014}_{-0.016}$	-	-



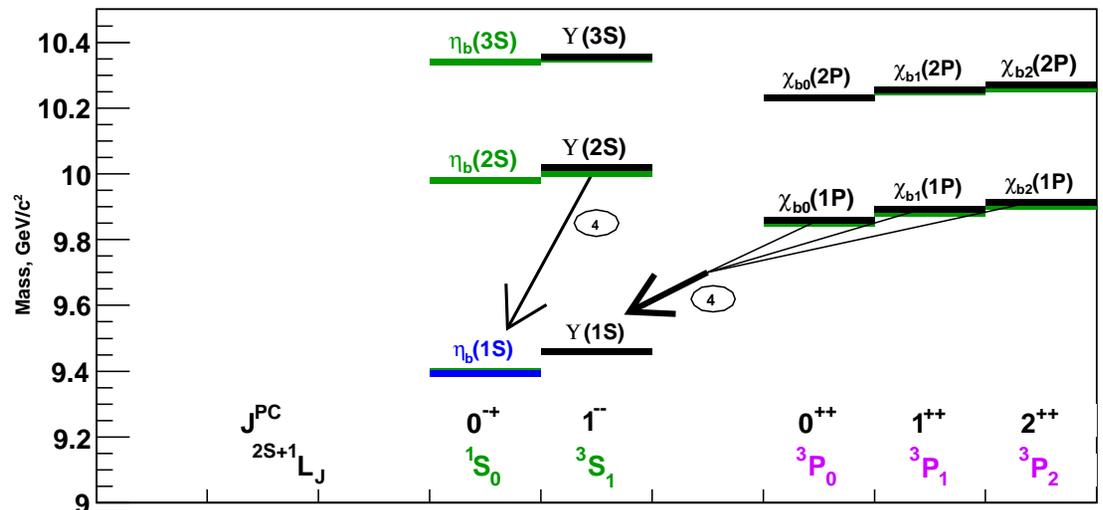


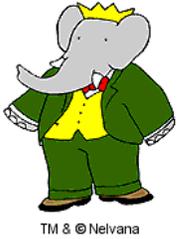
Radiative transitions from $\Upsilon(2S, 3S)$ with converted photons

- Fourth region of interest: $\chi_{bJ}(1P) \rightarrow \gamma\Upsilon(1S)$ and $\Upsilon(2S) \rightarrow \gamma\eta_b(1S)$
- **Left plots:** before (top) and after (bottom) background subtraction
- Clearly seen peaks for $\chi_{bJ}(1P)$ and even a hint for $\eta_b(1S)$ (inset)



Transition	E_γ^* (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%)				
				BABAR	CB	CUSB	CLEO	
$\chi_{b0}(1P) \rightarrow \gamma\Upsilon(1S)$	391.5	391 ± 267	0.496	$2.3 \pm 1.5^{+1.0}_{-0.7} \pm 0.2$	< 4.6	< 5	< 12	1.7 ± 0.4
$\chi_{b1}(1P) \rightarrow \gamma\Upsilon(1S)$	423.0	12604 ± 285	0.548	$36.2 \pm 0.8 \pm 1.7 \pm 2.1$	34 ± 7	40 ± 10	33.0 ± 2.6	
$\chi_{b2}(1P) \rightarrow \gamma\Upsilon(1S)$	442.0	7665^{+270}_{-272}	0.576	$20.2 \pm 0.7^{+1.0}_{-1.4} \pm 1.0$	25 ± 6	19 ± 8	18.5 ± 1.4	
$\Upsilon(2S) \rightarrow \gamma\eta_b(1S)$	$613.7^{+3.0+0.7}_{-2.6-1.1}$	1109 ± 348	1.050	$0.11 \pm 0.04^{+0.07}_{-0.05} (< 0.22)$	-	-	-	



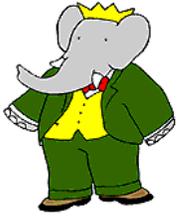


Radiative transitions from $\Upsilon(2S, 3S)$ with converted photons

Comparison of branching fractions
(as measured by BABAR in this analysis)
to theory predictions:

Decay	BABAR(%)	Theory (%)
$\mathcal{B}(\chi_{b0}(2P) \rightarrow \gamma\Upsilon(2S))$	(< 2.9)	1.27
$\mathcal{B}(\chi_{b1}(2P) \rightarrow \gamma\Upsilon(2S))$	19.1 ± 2.3	20.2
$\mathcal{B}(\chi_{b2}(2P) \rightarrow \gamma\Upsilon(2S))$	8.2 ± 1.4	10.1
$\mathcal{B}(\chi_{b0}(2P) \rightarrow \gamma\Upsilon(1S))$	(< 1.2)	0.96
$\mathcal{B}(\chi_{b1}(2P) \rightarrow \gamma\Upsilon(1S))$	9.9 ± 1.1	11.8
$\mathcal{B}(\chi_{b2}(2P) \rightarrow \gamma\Upsilon(1S))$	$7.1_{-0.9}^{+1.0}$	5.3
$\mathcal{B}(\chi_{b0}(1P) \rightarrow \gamma\Upsilon(1S))$	(< 4.6)	3.2
$\mathcal{B}(\chi_{b1}(1P) \rightarrow \gamma\Upsilon(1S))$	36.2 ± 2.8	46.1
$\mathcal{B}(\chi_{b2}(1P) \rightarrow \gamma\Upsilon(1S))$	$20.2_{-1.8}^{+1.6}$	22.2

Most of the numbers are compatible with each other



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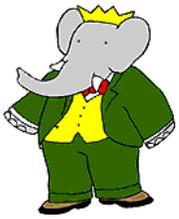


Search for $\Upsilon(3S) \rightarrow \pi^0 h_b(1P)$

First observation of $h_b(1P)$ (brilliantly confirmed by Belle)

Analysis strategy:

- Use BABAR's $\Upsilon(3S)$ sample (122×10^6 events)
- Look for sequential decay $\Upsilon(3S) \rightarrow \pi^0 h_b(1P), h_b(1P) \rightarrow \gamma \eta_b(1S)$
 - $\mathcal{B}(\Upsilon(3S) \rightarrow \pi^0 h_b(1P)) \approx 0.1\%$ (isospin-violating)
 - E1-transition: $\mathcal{B}(h_b(1P) \rightarrow \gamma \eta_b(1S)) \approx 40\text{-}50\%$
- Split sample into 3 MeV/c^2 -wide bins in $m_{recoil}(\pi^0)$
 - Reminder: $m_{recoil}(\pi^0) = \sqrt{(\sqrt{s} - E(\pi^0)_{CM})^2 - (\vec{p}(\pi^0)_{CM})^2}$
- Fit $m(\pi^0)$ distribution in each bin to obtain π^0 yield
- Plot π^0 yield versus $m_{recoil}(\pi^0)$
- Small signal is expected at around $9.9 \text{ GeV}/c^2$ on top of very large background
- Facilitate the search by requiring a photon with an energy corresponding to $h_b(1P) \rightarrow \gamma \eta_b(1S)$ decay
- Similar approach by CLEO and BES: $\psi(2S) \rightarrow \pi^0 h_c(1P), h_c(1P) \rightarrow \gamma \eta_c(2S)$



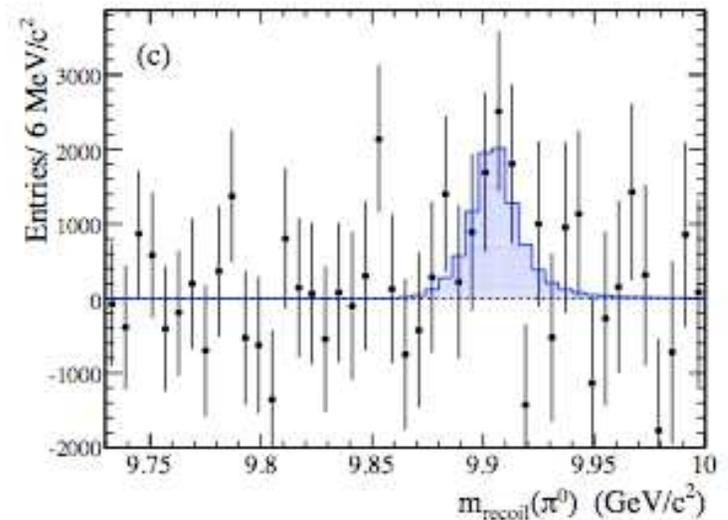
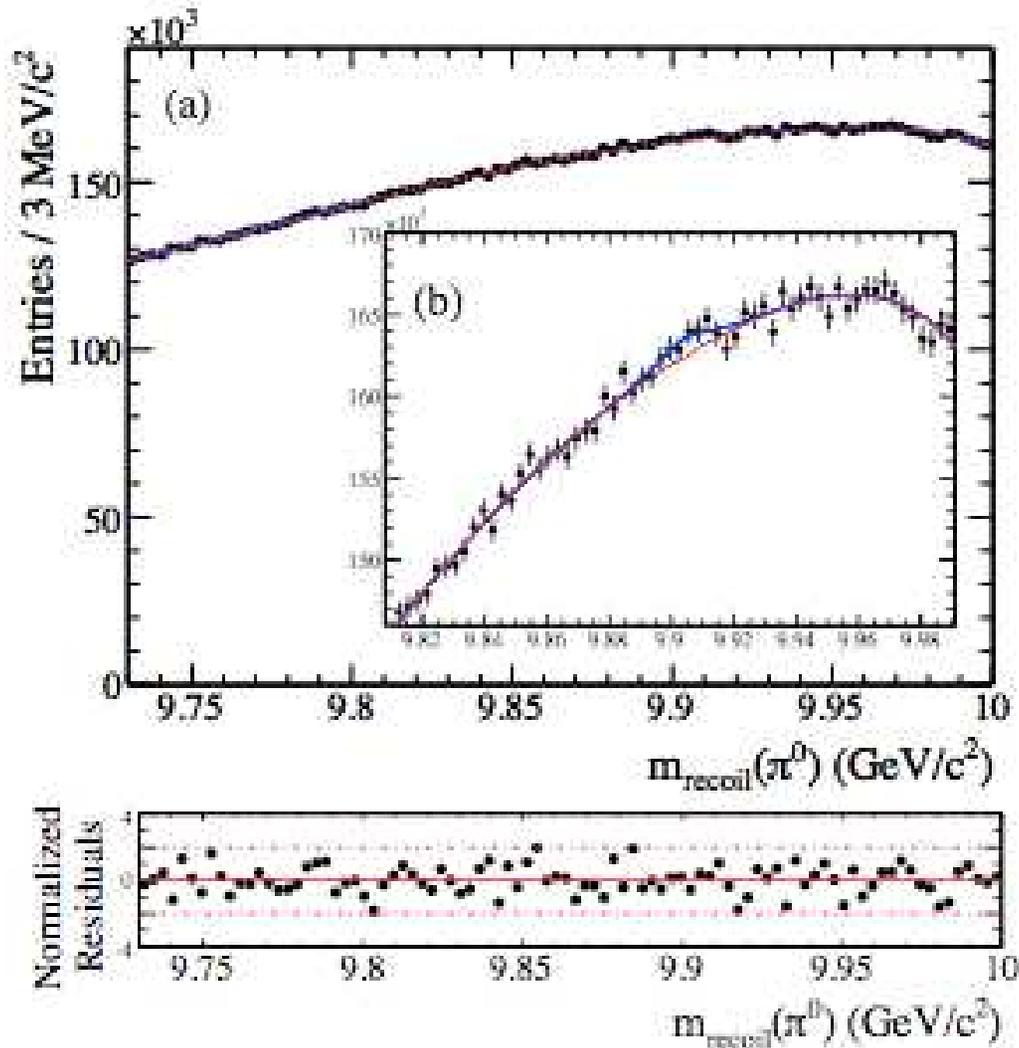
Search for $\Upsilon(3S) \rightarrow \pi^0 h_b(1P)$

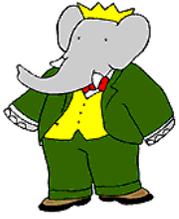


☞ **Left plots:**

- $m_{recoil}(\pi^0)$ distribution
- Inset: expanded signal region
- Bottom band: fit residuals

☞ **Bottom plot:** background-subtracted $m_{recoil}(\pi^0)$ dist.



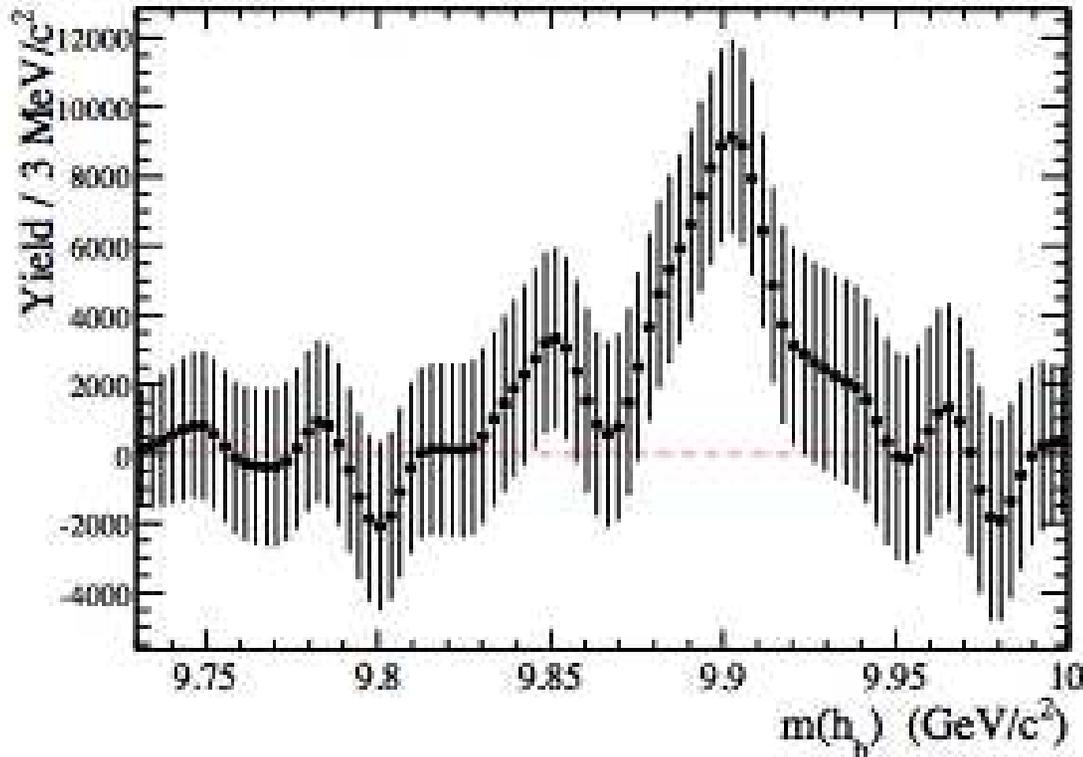


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Search for $\Upsilon(3S) \rightarrow \pi^0 h_b(1P)$

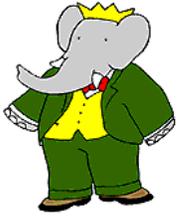
Fitted yield as a function of fixed $h_b(1P)$ mass:



$$m(h_b(1P)) = 9902 \pm 4(\text{stat.}) \pm 1(\text{syst.}) \text{ MeV}/c^2$$

$$\mathcal{B}(\Upsilon(3S) \rightarrow \pi^0 h_b(1P)) \times \mathcal{B}(h_b(1P) \rightarrow \gamma \eta_b(1S)) = (3.7 \pm 1.1(\text{stat.}) \pm 0.7(\text{syst.})) \times 10^{-4}$$

$$\mathcal{B}(\Upsilon(3S) \rightarrow \pi^0 h_b(1P)) \times \mathcal{B}(h_b(1P) \rightarrow \gamma \eta_b(1S)) < 5.8 \times 10^{-4} \text{ at C.L. } 90\%$$



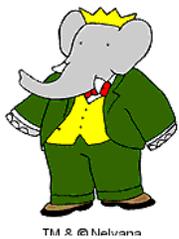
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Search for $\Upsilon(3S) \rightarrow \pi^+ \pi^- h_b(1P)$



Analysis strategy and by-products:

- ➡ Use $\Upsilon(3S)$ sample (122×10^6 events)
- ➡ Look for the decay $\Upsilon(3S) \rightarrow \pi^+ \pi^- h_b(1P)$ as a peak in $m_{recoil}(\pi^+ \pi^-)$
- ➡ As a by-product measure BF:
 - $\mathcal{B}(\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(2S)) = (3.00 \pm 0.02(\text{stat.}) \pm 0.14(\text{syst.}))\%$
 - More precise than world-average (2.45 ± 0.23)%
 - $\mathcal{B}(\Upsilon(3S) \rightarrow X \chi_{b1}(2P)) \times \mathcal{B}(\chi_{b1}(2P) \rightarrow \pi^+ \pi^- \chi_{b1}(1P)) =$
 $= (1.16 \pm 0.07(\text{stat.}) \pm 0.12(\text{syst.})) \times 10^{-3}$
 - $\mathcal{B}(\Upsilon(3S) \rightarrow X \chi_{b2}(2P)) \times \mathcal{B}(\chi_{b2}(2P) \rightarrow \pi^+ \pi^- \chi_{b2}(1P)) =$
 $= (0.64 \pm 0.04(\text{stat.}) \pm 0.08(\text{syst.})) \times 10^{-3}$
 - $\mathcal{B}(\Upsilon(3S) \rightarrow X \Upsilon(2S)) \times \mathcal{B}(\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S)) =$
 $= (1.78 \pm 0.02(\text{stat.}) \pm 0.11(\text{syst.}))\%$
 - $m(\Upsilon(3S)) - m(\Upsilon(2S)) = 331.50 \pm 0.02(\text{stat.}) \pm 0.13(\text{syst.}) \text{MeV}/c^2$



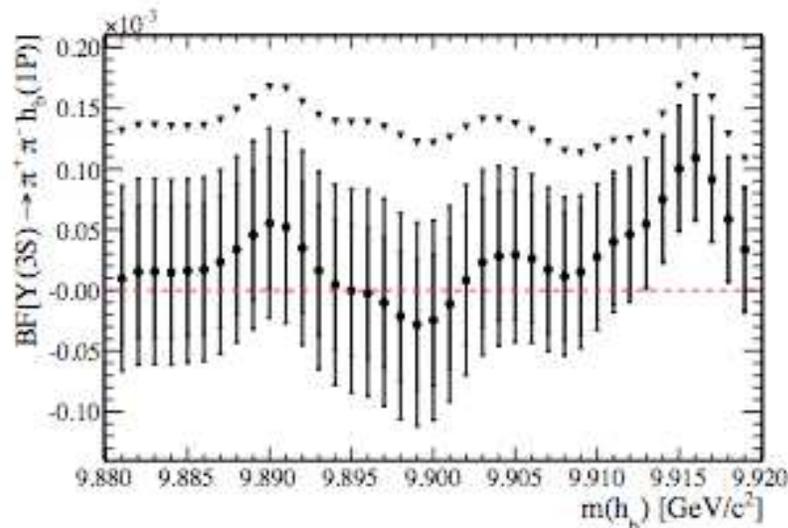
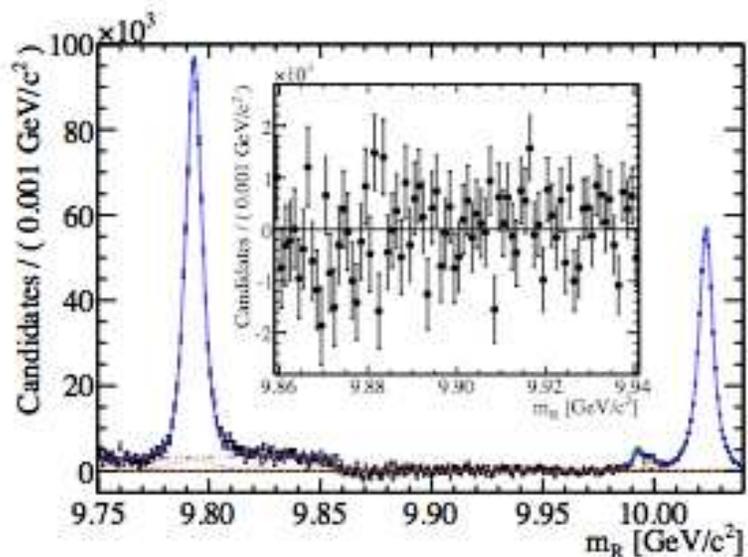
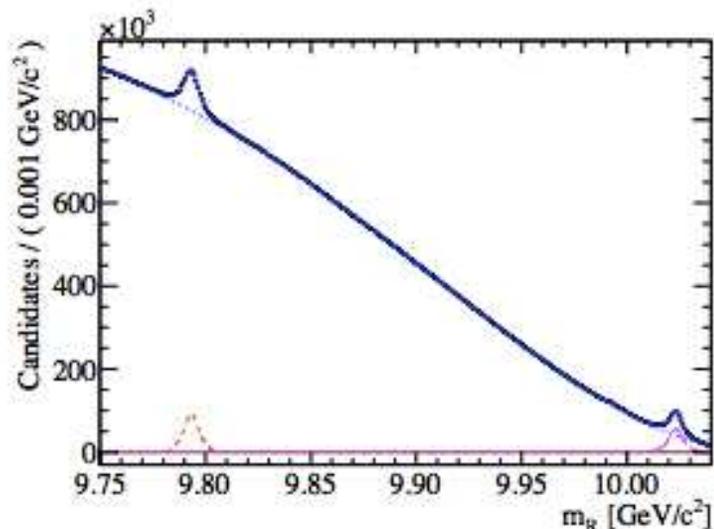
Search for $\Upsilon(3S) \rightarrow \pi^+ \pi^- h_b(1P)$

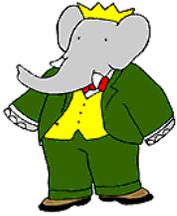
Left plots:

- Full (top) and background-subtracted (bottom) $m_{recoil}(\pi\pi)$
- Inset: expanded signal region

Bottom plot:

- Fitted yield as a function of fixed $h_b(1P)$ mass
- Triangles – 90% C.L. upper limits





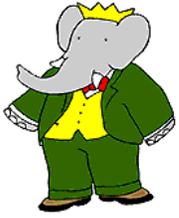
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Conclusion



- BABAR data provide a wonderful opportunity for many spectroscopic (and other, such as searches for light Higgs and Dark Matter) analyses
- Analyses involve both charmonium and bottomonium states
- Analyses involve both improvements of existing measurements and searching for new particles
- Many new exciting results are coming!!!

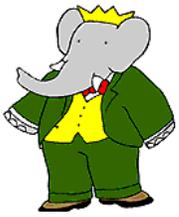
Stay tuned and thank you
for your attention!



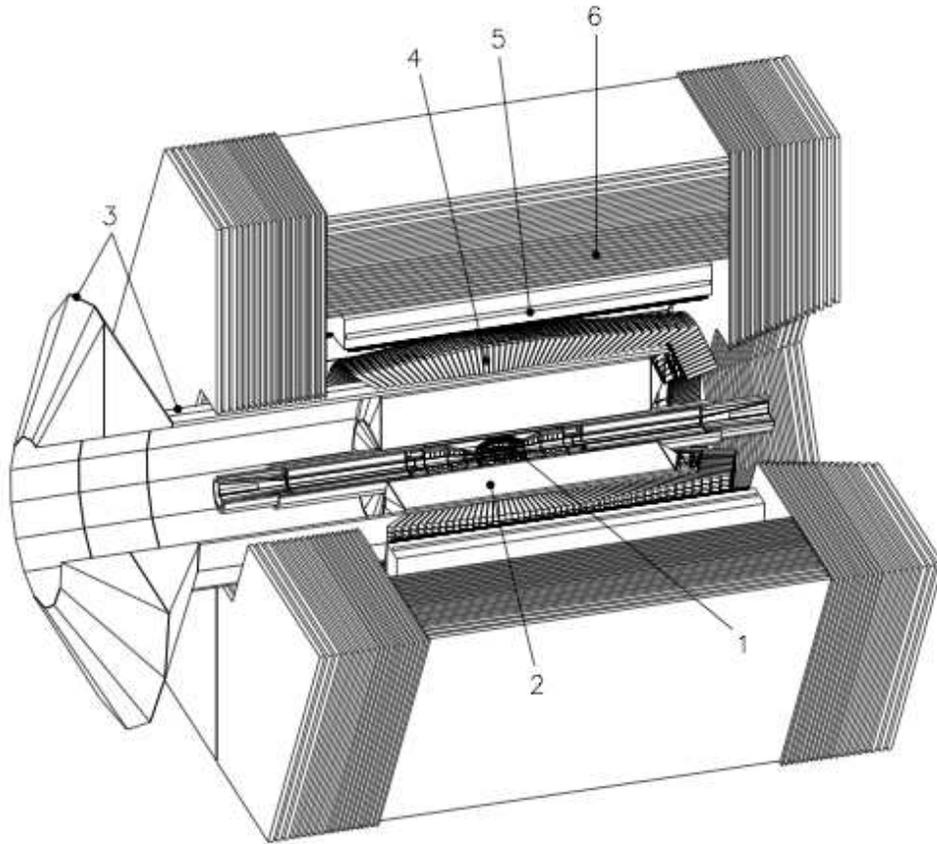
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Backup



BABAR detector



- 1) Silicon Vertex Tracker (SVT)
- 2) Drift Chamber (DCH)
- 3) Cherenkov Detector (DIRC)
- 4) Electromagnetic Calorimeter (EMC)
- 5) Magnet Coil
- 6) Instrumented Flux Return (IFR)

9-GeV electrons enter from the left side, 3-GeV positrons – from the right side